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Provenance Interpretation and Depositional Environment of Sandstones of the Ajali Formation, South of Ifon, Western Flank of Anambra Basin, Southwestern Nigeria

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ABSTRACT: Grain size analysis, heavy mineral analysis, and petrographic studies of sandstones of the Ajali Formation near Imoru (south of the Ifon), the western flank of the Anambra Basin, were conducted to determine the provenance and depositional environment. The textural attributes of the Ajali Sandstone were inferred from the statistical variables namely graphic mean, graphic kurtosis, inclusive graphic standard deviation (sorting), inclusive graphic skewness with values of 0.37 - 1.17 (average 0.55Ø), -9.84 - 3.07 (average 0.09Ø), 0.05 - 1.02 (average 0.75Ø), and -0.03 - 1.00 (average 0.35Ø) respectively. Bivariate plots, such as simple skewness measure versus standard deviation (sorting) and mean versus sorting, suggest that the Ajali Sandstone is mainly a fluvial environment. The petrographic result indicates that quartz is the dominant detrital component with iron oxide, and hematite and goethite are the major cement in the analyzed sandstone sample. The zircon–tourmaline–rutile (ZTR) indices range from 67.65% to 73.17%, indicating that the sandstones are sub-mature to mature. Provenance indicators support igneous rocks of acidic compositions (e.g., granite) and high-grade metamorphic rocks (e.g., granite gneiss) of the Basement Complex of Southwestern Nigeria.

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The Upper Cretaceous Ajali Formation is predominantly sandstone and extends across the Anambra Basin Ajali Sandstone is also called false-bedded sandstone (Reyment, 1965) and has a lateral extent that suggests a sheetlike geometry (Ladipo, 1985). Maximum recorded thickness is from the Igbariam-1 well, where the sandstone is up to 534 m thick (Tamfu, 1982; Oluwajana and Ehinola, 2016) but decreases gradually towards the west and east to only a few tens of meters around Okigwe (Ladipo, 1985). The depositional environment of the Ajali Formation on the eastern part of the Anambra Basin has been discussed by various authors namely Reyment 1965; Murat, 1972, Hoque and Ezepue, 1977; Agagu, 1975; Ladipo, 1986, although the environment of deposition of the Ajali Formation has been controversial. Some authors have suggested a fluvio-deltaic origin for the Ajali Sandstone (Reyment 1965, Murat, 1972; Hoque and Ezepue, 1977), while Agagu (1975) suggested a fluvial origin, possibly braided stream for the Ajali Sandstone. Ladipo (1986) inferred that the Ajali Sandstone was deposited under the tidally influenced regime, possibly tidal shelf, characterised by shoreline-parallel sand bodies with intercalations of shelf muds. Nwajide and Ladipo (1991) attributed certain internal structures as suggesting a shallow marine depositional environment, dominated by sand wave bedforms. However, reports on the depositional environment and provenance of sands of the Ajali Formation on the western flank of the Anambra Basin, south of Ifon are limited. Many researchers have conducted different studies on sediments in different

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parts of the world to interpret the depositional process and environment of such sediments (Ocheli *et al*., 2018). The grain-size distribution of sediment reflects both the hydrodynamic conditions and the grain-size population of sediments available from the source area (Bjørlykke, 2010). Therefore, the objective of this study is to investigate the provenance and depositional environment of the sandstone of the Ajali Formation near Imoru, south of the Ifon, western flank of the Anambra Basin, southwestern Nigeria

MATERIALS AND METHODS

Study Area: The Upper Cretaceous Ajali Formation across the Anambra Basin (Figure 1) and the depositional environment and provenance of sands of the Ajali Formation on the western flank of the Anambra Basin, south of Ifon (Figure 2) are the areas of study.

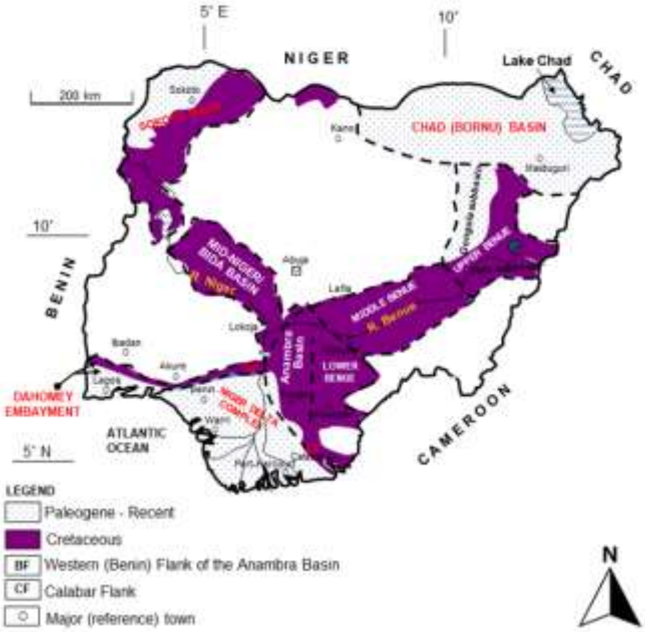

Fig 1. Map of Nigeria showing the different sedimentary basins, and the position of the western flank of the Anambra Basin (after Obaje *et al*. 2004)

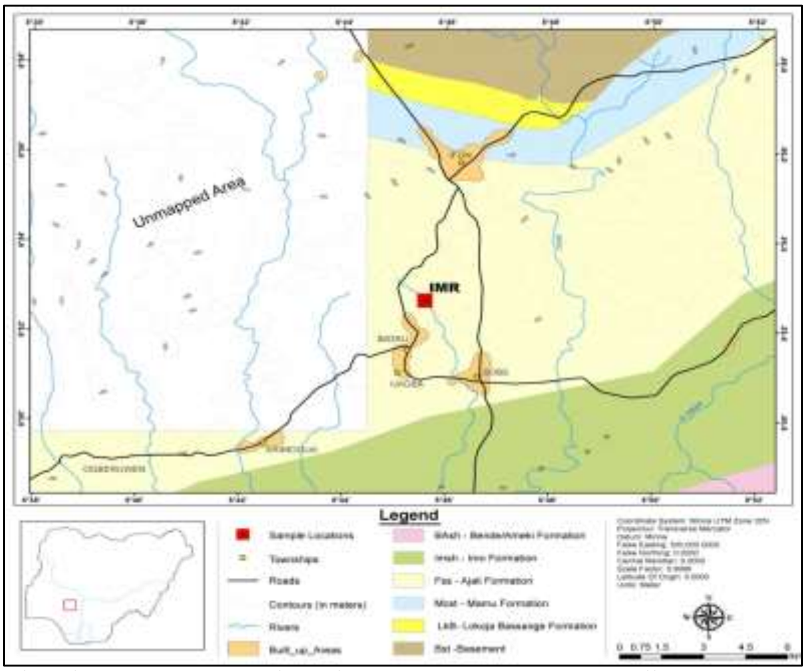

Fig 2. Geological Map of the Ifon area on the western flank of the Anambra Basin showing the different sedimentary units and the location of the outcrop exposure (Murat, 1969; Rahaman *et. al*., 2012).

Geologic Setting of The Study Area: The Anambra Basin developed during the thermal sag phase of the Benue Trough evolution, which formed following the plate-wide inversion tectonics that occurred in the Santonian and possibly continued into the Maastrichtian in the Northern Benue Trough and Chad Basin (Nwajide, 2013; Edegbai *et al*., 2019). The Anambra Basin is about 55,000 km^2 in size and is bordered to the west, east, and south by the Benin hinge line (Okitipupa Ridge), the Southern Benue Trough and the Oban Massif, and the Niger Delta Basin, respectively (Edegbai *et al*., 2019). Anambra Basin received sediments from the growing Abakaliki Anticlinorium; as a result, the basin was subsequently filled with Cretaceous-Paleogene sediments (Mode, 2004). The Campanian to Maastrichtian Lokoja Bassa'Nge, the Lower to Middle Maastrichtian Mamu, the Late Maastrichtian Ajali Formation, and the Nsukka Formation make up the stratigraphic succession of the western flank of the Anambra Basin (Figure 3). On the western side of the Anambra Basin, the Lokoja Bassa'Nge Formation unconformably overlies the Pre-Cambrian Basement Complex (Tattam, 1944). The Formation mostly comprises pebbly sands, cross-bedded sandstones, and coarse basal grits, with intercalations of sandy clays (Baggelaar *et al*., 1954). The Mamu Formation overlies the Lokoja Bassa'Nge Formation unconformably. Shales and sandstones make up the main lithologic associations of the Mamu Formation, with small occurrences of limestone beds in the south and coal seams in the central to upper portions of the basin (Ezeh *et al*., 2022). The Ajali Formation is compositionally super-mature (quartz arenites), medium to coarse-grained, well to moderately sorted, and friable.

Methodology: Ten (10) sandstone samples obtained from an outcrop section near Imoru were subjected to grain size and heavy mineral analyses. For the grain size study, 100g of each sample was disaggregated with a porcelain mortar and pestle and then sieved for 15 minutes following standard methods (Folk, 1974). The statistical parameters such as graphic mean (M_z), inclusive graphic standard deviation (σ_1), skewness (Sk_i), and kurtosis (K_G) were determined using standard formulae (Folk and Ward, 1957).

$$M_z \text{ (Graphic mean)} = \frac{\emptyset 16 + \emptyset 50 + \emptyset 84}{3} \quad \ldots\ldots 1$$

Inclusive graphic standard deviation

$$\sigma_1 = \frac{\emptyset 84 - \emptyset 16}{4} + \frac{\emptyset 95 - \emptyset 5}{6.6} \quad \ldots 2$$

$$SKi = \frac{\emptyset 16 + \emptyset 84 - 2\emptyset 50}{2(\emptyset 84 - \emptyset 16)} + \frac{\emptyset 5 + \emptyset 95 - 2\emptyset 50}{2(\emptyset 95 - \emptyset 5)} \quad (3)$$

Where SK_i = Skewness

$$\text{Graphic kurtosis } (K_G) = \frac{\emptyset 95 - \emptyset 5}{2.44(\emptyset 75 - \emptyset 25)} \quad \ldots\ldots 4$$

Where: $\emptyset_n$ is the n^{th} percentile of the size distribution taken from the cumulative frequency curve; Φ is the weight of sediment per size class as a percentage of the total sample weight

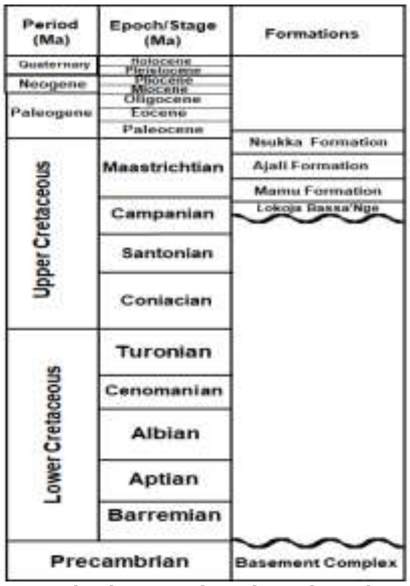

Fig 3. The generalized stratigraphic column shows the Cretaceous Formations in the western flank of the Anambra Basin, Nigeria (Ladipo, 2018).

Ten grams (10 g) of the samples that passed through 80 mesh-size sieves were taken for the heavy minerals separation by adopting the standard technique (Lindholm, 2012) using bromoform (specific gravity = 2.89 unit?). The recovered heavy minerals were cleaned, dried, and mounted on glass slides with Canada balsam. The heavy minerals were identified, and the ZTR (zircon-tourmaline-rutile) maturity index was calculated. Each sandstone sample was impregnated with blue-dyed epoxy resin and prepared to a thickness of 30 µm for optical examination. The thin section was studied under a transmitted-light microscope equipped with a camera. To distinguish hematite and goethite easily, iron-cemented samples were studied under oil immersion with a reflected-light microscope (Kettanah *et al*., 2015; Oksuz and Kocak, 2016; Adamolekun *et al*., 2023).

Field Observations: The outcrop exposure near Imoru is about 23.5 m thick, consisting of sandstone (20 m thick), an iron-rich band (0.7 m thick), and shale (0.3 m). The grey fissile shale is at the lower part of the section and is overlain by thick ferruginized sandstone (Fig. 4; Oluwajana, 2021).

The outcrop section consists of medium to coarse-grained, moderately sorted, indurated, and ferruginized sandstone. The sandstone is iron-cemented and characterized by sedimentary structures that include parallel-stratification, cross-stratification, and animal burrows.

Fig 4. The densely vegetated outcrop section at Imoru, south of Ifon (A), Parallel stratified sandstone of the Ajali Formation (B), Grey shale underlies the iron-rich band (C).

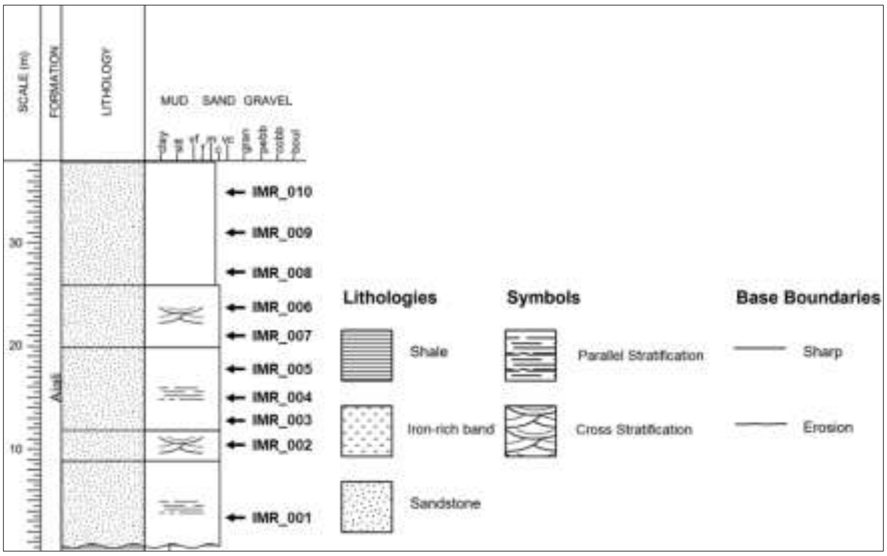

Fig 5. Stratigraphic column of the outcrop of Ajali Formation in the western Anambra Basin. "IMR_001" to "IMR_010" are the sample numbers

Grain Size Statistics: Table 1 shows the results obtained from the statistical computations of grain size distribution for the recovered sandstone samples. The graphic mean size (M_z) of the samples varies between - 0.37Ø to 1.17Ø (average, 0.55Ø), which indicates the predominance of coarse-grained sands (Folk and Ward, 1957). The standard deviation (σ_1) which is a measure of the sorting (Folk, 1974) ranges from 0.5 to 1.02 (Ave.: 0.75). Seventy per cent of the samples are moderately sorted sands (σ_1= 0.75 to 1.00), while 30% are moderately well-sorted sands (σ_1= 0.54 to 0.65).

Skewness of the distribution indicates whether the grain-size histogram is symmetrical or skewed to a higher percentage of coarser or finer material (Nichols, 2009). The skewness values range between -0.03 and 1.0 with a mean value of 0.35. Such skewness ranges indicate nearly symmetrical to very fine skewed (Blatt *et al*., 1991). Kurtosis is a value that indicates whether the histogram has a sharp peak or a flat top (Pettijohn, 1975). Calculated graphic kurtosis (K_G) values varying from -9.04 to 1.56 (average, 0.09). About 60% of the samples are leptokurtic, 10% extremely leptokurtic and 30% platykurtic (Table 1).

Heavy Mineral Analysis: The heavy mineral assemblage of the Ajali sandstones comprises transparent minerals such as zircon, rutile, tourmaline sillimanite, garnet, apatite, and opaques (Table 2). Statistical evaluation reveals that zircon makes up 8 to 10%, rutile makes up 7 to 11%, and tourmaline accounts for 8 to 11%. Other transparent heavies such as sillimanite (3 to 5%), garnet (3 to 4%), and apatite (2 to 5%) are present in trace amounts.

Table 1. Grain size statistical parameters of the sandstone samples of Ajali Formation

**In the yellow marked provide the proper symbol

SN	$Ø_5$	$Ø_{16}$	$Ø_{25}$	$Ø_{50}$	$Ø_{75}$	$Ø_{84}$	$Ø_{95}$	Mean (M_z)	Kurtosis (σ_1)	Standard deviation (K_G)	Skewness (SK_i)	Description
IMR_01	0	0	0.7	0.3	1.1	1.4	3	0.57	3.07	0.80	0.69	Coarse-grained, moderately sorted, strongly fine skewed, extremely leptokurtic.
IMR_02	0	-0.8	0.2	0.6	1	1.3	1.8	0.37	0.92	0.80	0	Coarse-grained, moderately sorted, near symmetrical, mesokurtic.
IMR_03	0	-0.6	0	0.6	1	1.2	2.4	0.40	0.98	0.81	0.08	Coarse-grained, moderately sorted, near symmetrical, mesokurtic.
IMR_04	0	-0.4	0.6	0.6	0.5	1.2	2.4	0.47	-9.84	0.76	0.13	Coarse-grained, moderately sorted, fine-skewed, very platykurtic.
IMR_05	0	-0.8	-0.2	0.5	1.2	1.4	2.1	0.37	0.61	0.87	0.17	Coarse-grained, moderately sorted, fine-skewed, very platykurtic.
IMR_06	0	0	0.1	1.1	1.2	2.4	2.8	1.17	1.04	1.02	0.15	Medium-grained, poorly sorted, fine-skewed, mesokurtic.
IMR_07	0	0	0.1	0.9	1.2	1.5	2.1	0.80	0.78	0.69	-0.03	Coarse-grained, moderately well-sorted, coarse-skewed, platykurtic.
IMR_08	0	0	0	0.3	0.8	1.2	2	0.50	1.02	0.60	0.60	Coarse-grained, moderately well sorted, strongly fine skewed, mesokurtic.
IMR_09	0	0	0	0	0.8	1.1	1.5	0.37	0.77	0.50	1.00	Coarse-grained, moderately well sorted, strongly fine skewed, mesokurtic.
IMR_10	0	0	0.4	0.2	0.9	1.4	1.9	0.53	1.56	0.64	0.75	Coarse-grained, moderately well sorted, strongly fine skewed, mesokurtic.
							Ave.	0.55	0.09	0.75	0.35	

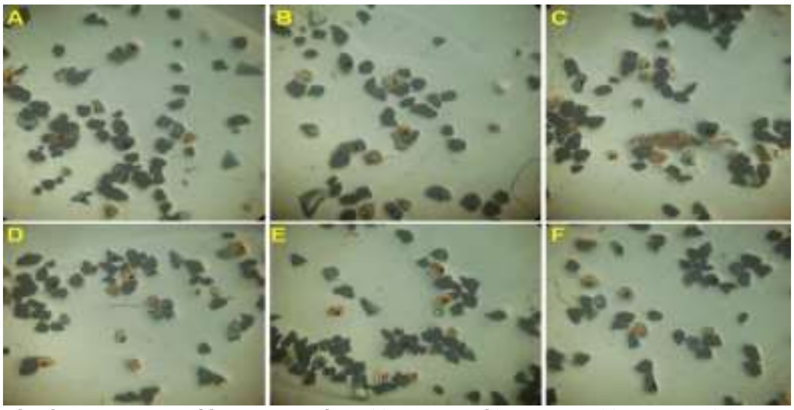

Fig 6. Photomicrographs showing recovered heavy minerals in (a) IMR_01, (b) IMR_O2, (c) IMR_05, (C) IMR_07, (d) IMR_08, and IMR_10. **Abbreviations:** Z – zircon**,** R **–** rutile, G – garnet, A – apatite, t – Tourmaline.

Table 2. Results of heavy mineral analysis of the sandstone samples recovered from an outcrop section near Imoru

Sample No	Zircon (%)	Rutile (%)	Tourmaline (%)	Sillimanite (%)	Garnet (%)	Apatite (%)	Opaque (%)	ZTR Index
IMR_01	10	8	11	4	3	4	23	72.50
IMR_02	8	10	9	3	4	4	22	71.05
IMR_03	9	10	11	4	4	3	23	73.17
IMR_04	10	9	9	4	3	4	22	71.79
IMR_05	9	9	11	5	4	2	24	72.50
IMR_06	8	7	8	4	3	4	22	67.65
IMR_07	9	9	10	4	4	5	23	68.29
IMR_08	9	10	9	4	4	3	21	71.79
IMR_09	9	11	10	5	2	4	23	73.17
IMR_10	10	9	10	4	3	4	21	72.50

Sandstone petrography: Quartz is the dominant detrital component in the analyzed sandstone sample (Table 3). The cement in the sandstone is iron oxide i.e., hematite and goethite (Table 3). The intergranular pore spaces are partly filled by the FeO_x cement, thus reducing the depositional porosity (Figures 7a and 7b). Only a few/negligible amounts of feldspar and rock fragments are present but were not encountered during the point counting.

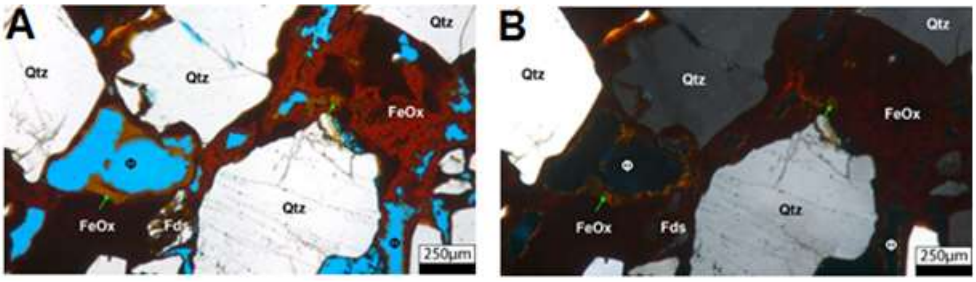

Fig 7. Photomicrographs of the detrital components of the siliciclastic sandstone. The left image is ppl while the right one is xpl. **Abbreviations:** Qtz = Quartz, Fds = Feldspar, Φ = porosity, FeO_x = Iron oxide. Green arrows = kaolinitic clay, red arrows = goethite (stain).

Provenance: The mineral grains are medium to coarse-grained, and subangular to subrounded indicating textural and mineralogical sub-mature to mature rocks, that have been transported a considerable distance from the source (Adeoye *et al*., 2022). The predominance of coarse-grained sediments in the studied section indicates that the sediments were deposited by strong currents or wave energy (Bjørlykke, 2010). The moderately sorted to moderately well-sorted sediments suggest that the sediments are far from the source (Boggs, 1987). The ZTR index ranges from 67.65% to 73.17% and suggests that the sandstone of the Ajali Formation is sub-mature to mature. Zircon euhedral and apatite presence indicates a silicic igneous source (Mout and Sarmah, 2021). Garnet and sillimanite indicate a high-rank metamorphic rock (Pettijohn, 1975). The occurrence of zircon, rutile, and tourmaline indicates that they may have been derived from igneous rocks of acidic compositions (e.g., granite), and high-grade metamorphic rocks (e.g., granite gneiss).

Table 3. Percentages from the total point count

Formation	**Ajali**
Location	**Imoru**
Sample Number(s)	**IMR-1ss**
Total Quartz	62.00
Total Feldspar	0.00
Total Rock Fragments	0.00
TOTAL QFR	62.00
Goethite (Pore Filling/Cement)	5.67
Hematite (Pore Filling/Cement)	16.33
Goethite (Pore Lining/Coat)	0.33
Hematite (Pore Lining/Coat)	3.67
Kaolinitic (Matrix)	0.00
Kaolinite (Vermiform)	0.00
Kaolinite (Cement)	0.00
FeO_x (Pore Filling/Cement undifferentiated)	1.33
FeO_x (Pore Lining/Cement undifferentiated)	0.00
Total Pore	**10.67**

According to Ogbahon and Opeloye (2014), Ajali sandstone on the western flank of the Anambra Basin (north of Ifon) are mineralogical mature and are derived mainly from acid igneous rocks, gneisses and older sandstones. Hoque (1977) has suggested, based on petrographic evidence, that some of the newly deposited sediments were also derived from the granitic basement of the Cameroonian Highlands weathered under humid tropical conditions. However, Hoque and Ezepue (1977) argued that the bulk of sandstone units of the Enugu, Mamu, Ajali, Nsukka, and Nanka Formations are distinguished by quartz arenites and are generally coarser than the sandstone units of the Asu River Group, the Odukpani, the Eze-Aku, and the Awgu Formations that are characterised by feldspathic arenites, hence the latter cannot be the only source of the former. The study area is bounded to the north by Basement Complex rocks of southwestern Nigeria, and therefore sands of the Ajali Formation, south of Ifon, may have been sourced derived from the granitic and gneiss complex of southwestern Nigeria.

Depositional Environment: The sandstone of the Ajali Formation is generally moderately sorted and positively skewed, these attributes suggest a deposition in the fluvial environment (Nichols, 2009; Boggs, 2009). The different bivariate plots such as simple skewness measure versus standard deviation (Sorting) and mean versus sorting (Figs. 8a and 8b) affirm deposition in a fluvial environment (Friedman and Sanders, 1978). Tijani *et al*., 2010 revealed that Ajali Sandstone in the Anambra Basin was deposited under a fluvial/river system-dominated sedimentary process. Ocheli *et al*. (2018) established a fluvial to shallow marine environment for the Ajali Sandstone in the western flank of the Anambra Basin. Ladipo (1985), Tijani *et al*., (2010), and Ogbahon and Opeloye (2014) observed that Ajali Sandstone has quartz greater than 90% with very little clay matrix, indicating a predominant basement source. Iron cementation is the most prominent authigenic process in the studied sandstone. Post-depositional staining of iron oxide on the Ajali Sandstone is widespread (Ladipo, 1985). The weathering and dissolution of iron-bearing minerals reported in the Precambrian Basement Complex of southern Nigeria have been considered the source of iron (Adamolekun *et al.*, 2023). The prolonged exposure at the surface in a humid environment is responsible for intense iron oxide (FeO_x) and iron oxyhydroxide (FeO(OH)) cementation (Adamolekun *et al*., 2023).

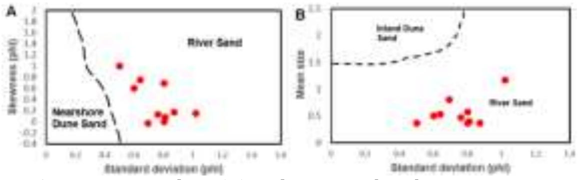

Fig 8. Bivariate plots. (A) Inclusive graphic skewness against standard deviation, (B) Mean grain size versus standard deviation.

Conclusions: The Ajali Sandstone, south of Ifon, is medium-to coarse-grained and moderately sorted, suggesting that the sediments were far from the source and were deposited by strong currents or wave energy. Bivariate plots indicate that the Ajali Sandstone is mainly of a fluvial environment. The ZTR index shows that the sandstone is sub-mature to mature. Provenance indicators support igneous rocks of acidic compositions (e.g., granite) and high-grade metamorphic rocks (e.g., granite gneiss) of the Basement Complex of Southwestern Nigeria.

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